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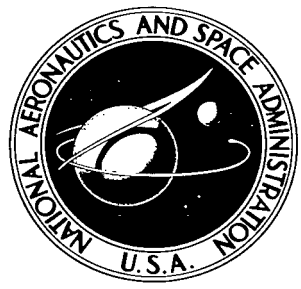

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FORMATION OF DETONATION WAVES IN HYDROGEN-OXYGEN MIXTURES FROM 0.2 TO 2 ATMOSPHERES INITIAL PRESSURE IN A 54-METER LONG TUBE

by Loren E. Bollinger

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OHIO STATE UNIVERSITY
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SUMMARY

Detonation induction distances and detonation velocities were determined in various hydrogen-oxygen mixtures in a 74-mm diameter detonation tube, 54 meters long. The initial pressures ranged from 0.2 to 2 atmospheres at ambient initial temperature.

Results show that the detonation velocities increase monotonically with increasing initial pressure for fuel concentrations between 30 and 85 per cent. Over this range of fuel concentrations, the detonation velocity rises with increasing hydrogen concentration to 85 per cent. The detonation velocity is not affected when the tube is open at both ends. Experimental values of detonation velocities obtained at one atmosphere initial pressure agree very well with theoretical values calculated previously; the maximum deviation is slightly in excess of one per cent. After a detonation wave stabilizes, its propagation rate does not vary over the length of the tube.

For all fuel concentrations between 45 and 75 per cent, the detonation induction distance increases as the initial pressure is reduced from one atmosphere down to at least 0.2 atmosphere. The minimum induction distance occurs at or near the stoichiometric mixture. At 0.2 atmosphere, the induction distance is more than three times that observed at atmospheric pressure.

Experimentally it was found that the flame propagation rate of mixtures containing different fuel concentrations was retarded near the end of the closed detonation tube, but remained essentially constant when the end was open to the atmosphere. A tentative explanation is that the shock wave, separated by an appreciable distance from the combustion wave of the detonation wave, reflects from the closed end of the tube and retards the oncoming combustion wave.

INTRODUCTION

Extensive studies of the formation of detonation waves in combustible gaseous mixtures have been made in the past ten years. Some of these investigations have been purely theoretical while others have combined theory with the results of experiments. References 1 to 48 are a selected group which illustrate the type of results which have been obtained; a few pertain to the study of the fully-established detonation wave.

The formation of detonations in mixtures of hydrogen and oxygen is of particular interest because of the technical importance of this propellant combination. Liquid hydrogen and liquid oxygen is a high-energy propellant system which is being developed for use in the rocket engines of a number of space boosters.

One of the problems associated with the utilization of liquid hydrogen and liquid oxygen is that of the possible development of an explosion or a detonation in the gaseous mixtures which result from venting and mixing after vaporization of the two liquids in their storage tanks because of unavoidable heat transfer. Under a number of circumstances it is feasible that the two gases may mix and attain explosive proportions somewhere in or about the vehicle. Ignition could occur from a number of sources.

The explosion limits of various mixtures of hydrogen and oxygen at atmospheric or reduced pressures are fairly well known (e.g., Ref. 49, p. 24) gives data for a stoichiometric mixture of hydrogen and oxygen from 1 to 10,000 mm Hg pressure and from 400 to 580°C; data are given for other fuel concentrations too. These explosion limits are known to be sensitive to the type and size of container and to the method of ignition.

From a practical viewpoint, it is quite feasible that a detonation could form in a mixture of hydrogen and oxygen, even at reduced pressure, if a source of ignition is present. Such mixtures could accumulate, at reduced pressure, in the open volume between the stages of a booster if both gases accidently leaked into this area. Structural damage could result from the high overpressure and temperature.

From previous experiments (Refs. 8, 15, 18, 19, 20, 34, 37 and 47), it was known that the detonation induction distances in hydrogen-oxygen mixtures decreased when the pressure was increased above one atmosphere; it was assumed, therefore, that initial pressures below one atmosphere would cause the induction distances to increase. To determine these distances, a long detonation tube was fabricated; it was used also with hydrogen-air mixtures which have rather long induction distances (Ref. 50). A long tube, 54 meters in length, was constructed and experiments were conducted to determine experimentally if any variation in the detonation velocity could be measured over this distance.

Experiments were conducted also to determine what effect the plate at the ignitor end of the tube has upon the formation of a detonation. Brinkley and Lewis (Ref. 51), in generalizing the classical work of Berthelot, state that a combustion wave propagating from an open toward a closed end of a cylindrical tube filled with an explosive mixture rapidly attains a steady velocity but does not accelerate to a detonation wave. Experimental results obtained in this study have shown that the ignitor end of the detonation tube does not have to be closed in order for a detonation to form in a hydrogen-oxygen mixture.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

All experiments were conducted in a 74-mm diameter inconel tube, 54 meters long, fabricated in 18 three-meter long sections (Fig. 1). Detection probes were spaced along the entire length approximately 60 cm apart. Ionization-type probes were employed to sense the passage of the flame front. A ten-channel electronic chronograph was used to measure the time intervals. Coverage of the entire tube was accomplished by conducting repeat experiments with the probe wires situated in different probe positions. All mixtures were ignited with Pyrofuze wire, 0.005-inch diameter, using a 28-volt DC power supply.

Time intervals were measured in steps of one microsecond. Physically, the tube was located outdoors because of its length. To protect the equipment during the winter, a wooden framework, covered with clear plastic, was built around the detonation tube. Electric heating wires were wound around the tube to provide sufficient heat to prevent freezing of the water vapor after an experiment and to facilitate flushing and evacuating the tube prior to initiating a new experiment. Thirty three coaxial cables, 200 feet long, connected probe wires to the chronograph. Although some cables could have been made shorter, it was essential to keep all of them the same length so that the voltage pulses from the probes would not be distorted because of a different capacitance load which results from the distributed capacitance of the coaxial cable.

The probe wires were made from #16 AWG copper wire that had been quadruple-coated by Teflon for insulation purposes. Ordinarily a 22.5-volt battery was connected between the coaxial cable and the probe wire. Occasionally higher voltages were employed at the lower values of initial pressure. An electrical circuit was completed when the flame passed a probe and momentarily shorted the probe wire to ground because of the electrical conduction properties of the flame. This voltage pulse, after transmission through the 200-foot long coaxial cable, was amplified by a pulse amplifier. The output signal then triggered a latching binary circuit which actuated an electronic gate between the precision oscillator signal and the 1-mc electronic counters. Accuracy of the crystal frequency was ensured by comparing the oscillator output signal with the carrier frequency of WWV, the standard time and frequency radio station operated by the National Bureau of Standards. In this area of the country and with the equipment used in the Laboratory, it is estimated that the accuracy of the local oscillator frequency used in the chronograph is accurate to at least 1 part in 5×10^8 on a relatively short term basis. Details of the chronograph are described in Refs. 5, 6 and 10.

The combustible mixture in the detonation tube was established by the following method. Known flow rates of hydrogen and oxygen were established by an appropriate control system. The individual gases were mixed thoroughly in a mixing vessel. Afterward, the mixture flowed through the detonation tube for a suitable length of time to ensure that the mixture was uniform and to make certain that all residual gases were removed. The tube was evacuated prior

to each experiment. For the studies at low pressures, the combustible mixture was pumped through the tube by a vacuum pump. Dry air was injected into the tube after each experiment to aid in the removal of the products of combustion. In all experiments, a sufficient quantity of gas flowed through the tube to displace its free volume many times. No attempt was made to control the initial temperature of the gas because it was found in previous experiments (Refs. 8 and 18) that the induction distance is relatively insensitive to the initial gas temperature as long as only room-temperature variations are involved. Hydrogen and oxygen were taken from standard cylinders. Manifold traps, containing silica gel, were used to remove moisture and oil. A freon refrigeration system maintained the silica gel at a low temperature to improve its efficiency.

Data taken in the region where the detonation wave was fully established were quite repeatable. Previously it had been found that the flame propagation rates were not repeatable in the initiation region, even for identical initial conditions of pressure, temperature, and composition. These variations in flame propagation rates in the induction zone probably result from turbulence conditions with associated "spikes" of flame shooting forward over a detonation probe, tilted flame fronts, or spinning flame fronts. Repeated experiments for the same initial conditions did not give the same results because of the random nature of the process.

In order to obtain useful and meaningful data under these conditions, it was necessary to conduct a number of experiments with identical initial conditions for the gas mixture. Values of the various flame propagation rates for each probe station were averaged and graphed as a function of the distance from the ignitor. Both the maximum and minimum values are indicated too. A detonation induction distance, based on the maximum flame propagation rates, was determined from the graphs as the point where the curve through the values of the maximum propagation rates first reaches the theoretical value, or experimental values if theoretical values are not available, of the detonation velocity for the particular set of initial conditions. Another induction distance, based on average values of the flame propagation rates, was determined in a similar manner.

DISCUSSION OF RESULTS

In general, three mixtures with different fuel concentrations were employed in the experiments to determine detonation induction distances. These mixtures had fuel concentrations of 45, 66.67 and 75 per cent. During the latter period of experimentation, a gas chromatograph was installed in the laboratory. After the chromatograph became operational, gas samples of the combustible mixtures were taken during each experiment and an analysis of the composition was made. Previously, it was necessary to depend solely on accurate calibration of the flowmeters. Results from the chromatographic analysis showed that the flowmeters could be calibrated sufficiently accurate for this type of experiment, but it is highly desirable to have an independent measurement of the composition.

Results of the experiments are presented in the following sections which are catagorized in terms of the initial pressure of investigation. The order of presentation of the results is not the order in which the experiments were conducted.

Initial Pressure = 0.2 Atm.

Experiments were conducted with mixtures of 45, 66.67, and 75 per cent hydrogen. Results, however, were obtained only with the stoichiometric mixture. At the other two fuel concentrations, the amount of ionization in the flame front was insufficient for the ionization-type detector probes to trigger the chronograph. Even with a stoichiometric mixture, no data could be obtained in much of the build-up region of the detonation wave. Therefore, it was necessary to estimate the induction distance. The data are shown in Fig. 2. There was no difficulty in obtaining the detonation velocity. Results are presented in Table 1. The induction distances are appreciably longer than those which have been measured at atmospheric pressure. The detonation velocity is somewhat lower than the theoretical value at atmospheric pressure (Ref. 33). This trend follows that which was obtained in the theoretical calculations which covered the range from 1 to 100 atmospheres initial pressure; the detonation velocity increases slightly with increasing initial pressure.

It can be seen from the graph of the data that the detonation wave requires an appreciable distance to stabilize at this reduced pressure. At higher values of initial pressure, stable detonation conditions are achieved in a shorter distance. This result, however, is not unexpected.

Initial Pressure = 0.3 Atm.

Only limited experiments were conducted at this value of initial pressure to determine the detonation velocity of a stoichiometric mixture. Data were taken between 43 and 49 meters distance from the ignitor to obtain the detonation velocity. The result is given in Table 1.

Initial Pressure = 0.4 Atm.

These experiments were essentially the same as those conducted at 0.3 atmosphere initial pressure. The detonation velocity is given in Table 1. For higher initial pressures, the detonation velocity rises slightly.

Initial Pressure = 0.5 Atm.

Induction distances were determined for fuel concentrations of 45, 66.67 and 75 per cent fuel. Results are given in Table 1. Results show that the minimum induction distance occurs at or near the stoichiometric mixture similar to the results obtained at higher initial pressures. These distances are shorter than those measured at 0.2 atmospheres initial pressure and longer than those determined at higher pressures. The trend is that the detonation induction distance decreases with elevated pressure as determined over the range from 0.2 to 25 atmospheres initial pressure. Data used in the determination of the detonation induction distances for the three mixtures are presented in Figs. 3-5.

After obtaining the necessary data to determine the induction distances, the probes were moved to a location near the end of the 54-meter long tube to measure the steady detonation velocity. Besides the detonation velocities obtained for 45, 66.67, and 75 per cent fuel mixtures, other experiments were conducted to obtain detonation-velocity data for mixtures containing 30, 40, 50, 60, 70, and 80 per cent fuel concentration. These velocities are given in Table 1 also; a graph, Fig. 6, was prepared to illustrate the dependence of detonation velocity upon fuel concentration. As can be seen from the curve of the data, very little scatter was present in the experimental values. A comparison of these experimental data with theoretical values of detonation velocities of similar mixtures at 1 atmosphere initial pressure shows that the latter values are higher but the trend is the same. This result was expected from both experimental and theoretical results obtained previously.

Initial Pressure = 1 Atm.

The initial experiments were conducted with fuel concentrations of 45, 66.67, and 75 per cent. Data from these experiments are presented in Figs. 7-9. The detonation induction distances for these three mixtures are given in Table 1. They are shorter than those obtained at the lower initial pressures; also these distances are longer than those obtained during previous experiments with smaller diameter tubes (Refs. 8, 18, 20 and 47). These induction distances, in a 74-mm diameter tube, agree rather well with those measured in a previous study in which a 79-mm diameter tube was employed (Ref. 47).

Detonation velocities were measured at locations between 35 and 40 meters from the ignitor for these three mixtures; additional data were obtained for fuel concentrations of 30, 40, 50, 60, 70, 80, and 85 per cent. These data are graphed in Fig. 6 along with those obtained at 0.5 atmosphere initial pressure. At all fuel concentrations, for one atmosphere initial pressure conditions, the experimental detonation velocities are higher than those obtained at 0.5 atmosphere initial pressure as anticipated. At higher values of initial pressure, more of the energy released is available to increase the gas temperature and propagation velocities because the amount of dissociation is reduced.

Theoretical values of detonation velocities at one atmosphere initial pressure (Ref. 33) fall practically on top of the curve drawn through the experimental data given in Fig. 6. For closer comparison, Table 2 was prepared. The theoretical values (Ref. 33) for fuel concentrations not calculated were extrapolated between those computed previously (30, 45, 55, 66.67, 75, 85, and 90 per cent fuel). These results show that the experimental values vary above and below the theoretical detonation velocities. The poorest agreement was at 45 per cent fuel concentration where the experimental value exceeded theoretical velocity slightly in excess of one per cent. In general, however, the agreement is excellent.

Induction distances determined at 0.2, 0.5 and 1 atmosphere initial pressure are graphed as a function of fuel concentration in Fig. 10. For the fuel concentrations employed, the induction distance is relatively insensitive to fuel concentration on the lean side of the stoichiometric value. Based on previous experiments with hydrogen-oxygen mixtures, the induction distances

probably will increase sharply for fuel concentrations leaner than 45 per cent hydrogen. Induction distances in fuel-rich mixtures generally increase faster than do those in fuel-lean mixtures and these data (Fig. 10) emphasize this generalization.

During the early portion of the experiments conducted with the 54-meter long tube, it was decided to make detailed measurements of the flame propagation rates along the entire tube length to see if any variation of the detonation velocity could be detected. A mixture containing 72 per cent hydrogen was employed. The results are given in Fig. 11. Neglecting the data obtained in the last five meters of tube length which are discussed later, it can be seen that the velocity does not vary. The minor variations in the propagation rate at specific locations along the tube length are attributed to discontinuities at the junctions of the tube sections. Although attempts were made to have smooth junctions, in some cases there were unavoidable minor discontinuities; these are associated with most of the variations indicated in Fig. 11.

When data were taken near the downstream end of the tube which was closed, it was found that the flame propagation rate dropped markedly as shown in Fig. 11. Numerous experiments were conducted to determine the validity of these data. Finally, experiments were conducted with the cover plate off. In this open-end tube configuration the propagation rate did not decrease (Fig. 11). When the cover plate was loosely coupled to the tube with tape, propagation rates were obtained whose values lie between those obtained with the cover plate on and off. Thus, it was shown that the retarding mechanism was generated by the cover plate of the detonation tube. Data for a mixture with 45 per cent hydrogen concentration also showed a retardation effect but not as marked as that obtained with the previous mixture (Fig. 12).

The mechanism which causes retardation of the detonation wave near the closed end of the tube is difficult to explain on the basis of these experimental results alone. A number of possibilities have been considered; to obtain adequate supporting data for any of these theories, however, more experimental investigation would be necessary using instrumentation specially designed to resolve this problem. One possible mechanism is discussed herein but the supporting argument is rather tenuous. Therefore, this explanation should be regarded as a tentative one until more studies are conducted to elucidate the mechanism.

The stable detonation wave is well-established long before it reaches the end of the 54-meter long tube. Since the detonation wave is composed of a shock wave followed by a combustion wave, the shock wave will reach the closed end of the tube before the combustion wave and reflect from the end. If there is an appreciable separation between the shock wave and the combustion wave, then the reflected shock would interfere with the combustion wave and cause a retardation, as observed experimentally. Little is known about the distance of separation between the shock wave and the combustion zone in a detonation wave. For the mixture containing 72 per cent hydrogen, the present experimental results indicate that the separation distance is approximately 7 to 10 meters. This amount of separation is somewhat difficult to accept, but, in view of the lack of knowledge of these values, the mechanism does appear to offer a feasible mechanism to produce the interference and retardation effect. The detector probes respond only to the presence of the flame and the ionized gases associated with it. The shock wave does not develop a sufficiently high temperature in the gases behind it to produce the ionization level required to trigger the sensor probes.

It does not appear feasible that the retardation effect could be generated as a result of mechanical oscillation of the cover plate. Because of the retonation wave striking the cover plate of the detonation tube at the ignitor end, a sound wave is propagated at a high speed through the metal walls of the tube. This disturbance reaches the cover plate at the downstream end of the tube prior to the detonation wave because of the high speed of transmission through the metal walls. If this disturbance causes the cover plate at the impact end to vibrate, weak sound waves probably are propagated toward the oncoming detonation wave. Shock waves could not be generated instead of sound waves because of the mass and inertia of the system. However, there is no mechanism which is obvious by which the sound waves could retard the combustion wave.

Obviously it will be necessary to conduct additional studies to explain this experimental observation.

The data depicted in Fig. 11 have been replotted in Fig. 13 in non-dimensional form. The actual flame propagation rate has been divided by the theoretical value of detonation velocity and the distance from the ignitor has been divided by the tube diameter. Thus, these data represent the deviation of the propagation rates from the theoretical values for a given number of pipe diameters distance from the ignitor. Where the theoretical or actual detonation velocities are known, it might

be more desirable to present data of this type in non-dimensional form in order to facilitiate comparison with data obtained in tubes of different diameter and with different combustible mixtures.

In Ref. 51 it is mentioned that Shuey, studying the detonation of acetylene at various pressures in long tubes with diameters ranging from 0.25 to 4.5 inches, found that a detonation wave was formed in all cases after the deflagration wave travelled a distance of about 60 tube diameters in the initially quiescent gas. Since data were available from past and present experiments, a check was made to see if similar results hold for various hydrogen-oxygen mixtures. Table 3 illustrates that the results found for pure acetylene do not agree with those obtained for hydrogen-oxygen mixtures. There is no consistent pattern evident from these various ratios for different initial conditions and tube diameters.

According to Berthelot as quoted by Brinkley and Lewis (Ref. 51) a detonation wave cannot be established in a straight cylindrical tube if both ends are open. The reasoning given is that no driving pressure force could be generated to form a shock if the product gases at the ignitor end of the tube could exhaust into the atmosphere rather than reflect from the cover plate. This assumption disregards the friction at the tube wall. Once the flame has propagated into the open tube there is sufficient friction to allow the formation of a shock wave ahead of the flame. Since this wave can form only after the flame has traveled a certain distance into the tube, the induction distance in this case must be longer than in a tube closed at the ignition end of the tube. In a short tube closed at both ends the induction distance should be shorter than in a long tube closed at both ends because of reflections of the shock wave from the closed end. To test this theory, a series of experiments were conducted with a stoichiometric mixture of hydrogen and oxygen in the 54-meter long tube. The cover plate at the ignitor was removed just prior to ignition. The downstream end of the tube was sealed with masking tape after filling operations were completed to prevent diffusion of air into the combustible mixture. When filling the tube with the mixture at the ignitor end, a paper covering was used to prevent diffusion by air. Then approximately three seconds prior to ignition, the thin paper was removed so that the tube was completely open. The ignitor wire was attached to two stiffer wires and inserted into the detonation tube approximately four to six inches.

The results obtained, Fig. 14, were as anticipated: All mixtures detonated without difficulty. The measured detonation velocity was identical to that obtained previously with a stoichiometric mixture in a completely closed tube. The induction distance as anticipated increased an appreciable amount as shown in Table 1. For the open-end tube, the induction distance was nearly twice as long as in the closed tube. Except for rather fuel-rich mixtures, the flame propagation rate ordinarily overshoots the stable detonation velocity during the transition phase from deflagration to detonation. When the cover plate at the ignitor end was removed, the amount of overshoot of the flame propagation rate was reduced over that obtained for closed-tube conditions.

Initial Pressure = 2 Atm.

A small number of experiments were conducted at this pressure level to ascertain the detonation velocities which are depicted in Fig. 6 and listed in Table 1. Values for all mixtures are higher than those obtained for one atmosphere pressure. No measurements were made to determine detonation induction distances.

CONCLUSIONS

From experimental measurements it was shown that the detonation velocities increase monotonically with increasing initial pressure for all fuel concentrations between 30 and 85 per cent. The increase is slight but quite definite. Up to 85 per cent hydrogen fuel concentration, the detonation velocity continues to rise without indication of reaching a maximum. It was shown too that the detonation velocity is not changed when the metal cover plates are completely removed from the tube prior to ignition. From the fact that a stoichiometric mixture detonated without difficulty, although with a greater induction distance, it can be concluded that the cover plate at the ignitor end is not necessary to create additional pressure waves to form the detonation wave. In addition to increasing the detonation induction distance, the absence of a cover plate reduces the overshoot in the transition region of the flame propagation rates. In closed tubes, this overshoot is quite extensive for many mixtures, especially for lean fuel concentrations.

From Table 2 it can be concluded that the experimental detonation velocities for fuel concentrations between 30 and 85 per cent at one atmosphere initial pressure agree very well with theoretical values calculated previously. The maximum deviation is only slightly in excess of one per cent, and that value occurred for only one mixture.

It can be concluded from these results that the detonation induction distance continues to increase, for all mixtures between 45 and 75 per cent hydrogen, from one atmosphere down to at least 0.2 atmosphere. There is no obvious reason to anticipate a change in this trend at still lower pressures. The minimum induction distance occurs near the stoichiometric mixture, as far as could be determined with the resolution utilized, as it did for initial pressures up to 25 atmospheres. There is less change in induction distance for lean mixtures than was obtained at initial pressures above one atmosphere.

It was shown experimentally that there is a retarding effect on the flame propagation rate near the closed end of a long tube which is not present with open-ended tubes. The tentative explanation offered is that the shock wave of the detonation wave reflects from the end of the tube and retards the oncoming combustion wave. From experimental data, this hypothesis requires that the shock wave and combustion wave of the detonation wave be separated by a rather large distance; in the case of a hydrogen-oxygen mixture containing 72 per cent hydrogen, the separation is approximately 7 to 10 meters. Ignition delay times in these mixtures, after compression by a shock wave, have not been measured for these conditions of pressure and temperature.

Detonation induction distances in hydrogen-oxygen mixtures cannot be approximated by a specific number of pipe diameters from the ignitor for various conditions of initial pressure and temperature in tubes of different diameter. With pure acetylene, Shuey has shown that the detonation is formed about 60 pipe diameters regardless of tube diameter. Data for hydrogen-oxygen mixtures show no consistent pattern.

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TABLE 1

EXPERIMENTAL DETONATION VELOCITIES AND INDUCTION DISTANCES

p_i (atm)	Mole Per Cent Fuel	Detonation Velocity (m/sec)	Induction Distance (cm)	
			A	B
0.2	66.67	2693	500*	550*
0.3	66.67	2727	-	-
0.4	66.67	2756	-	-
0.5	30	1821	-	-
0.5	40	2042	-	-
0.5	45	2169	270	320
0.5	50	2278	-	-
0.5	60	2570	-	-
0.5	66.67	2786	245	260
0.5	70	2906	-	-
0.5	75	3112	360	380
0.5	80	3320	-	-
1	30	1840	-	-
1	40	2065	-	-
1	45	2208	160	170
1	50	2310	-	-
1	60	2602	-	-
1	66.67	2850	150	160
1	70	2980	-	-
1	75	3181	210	220
1	80	3394	-	-
1	85	3609	-	-
1	66.67**	2852	270	320
2	30	1843	-	-
2	40	2083	-	-
2	50	2347	-	-
2	60	2639	-	-
2	66.67	2873	-	-
2	70	2993	-	-
2	80	3449	-	-
2	85	3639	-	-

* - Estimated.
** - Both cover plates on detonation tube removed.
A - Based on maximum flame propagation rates.
B - Based on average flame propagation rates.

TABLE 2

COMPARISON OF EXPERIMENTAL DETONATION VELOCITIES AND THEORETICAL VALUES FOR HYDROGEN-OXYGEN MIXTURES AT 1 ATMOSPHERE INITIAL PRESSURE

Mole Per Cent Fuel	Theoretical Velocity* (m/sec)	Experimental Velocity (m/sec)	Deviation of Experimental Value From Theoretical (per cent)
30	1845	1840	-0.27
40	2065	2065	0
45	2182	2208	+1.19
50	2315	2310	-0.22
55	2459	-	-
60	2610	2602	-0.31
66.67	2826	2850	+0.85
70	2965	2980	+0.51
75	3173	3181	+0.25
80	3400	3394	-0.18
85	3627	3609	-0.50
90	3796	-	-

* From Ref. 33

TABLE 3

RATIOS OF DETONATION INDUCTION DISTANCE TO TUBE DIAMETER FOR VARIOUS HYDROGEN-OXYGEN MIXTURES*

p_i atm	Per Cent Fuel in Mixture	Tube Diameter (mm)			
		15	50	74	79
0.2	66.67	-	-	6.75	-
0.5	45	-	-	3.65	-
0.5	66.67	-	-	3.31	-
0.5	75	-	-	4.86	-
1	45	5.47	2.12	2.16	2.35
1	66.67	4.93	1.44	2.03	1.73
1	75	6.30	3.30	2.84	2.62
5	45	1.93	-	-	1.09
5	66.67	1.27	-	-	0.47
5	75	2.30	-	-	1.14

* Data from Ref. 47 and present study.

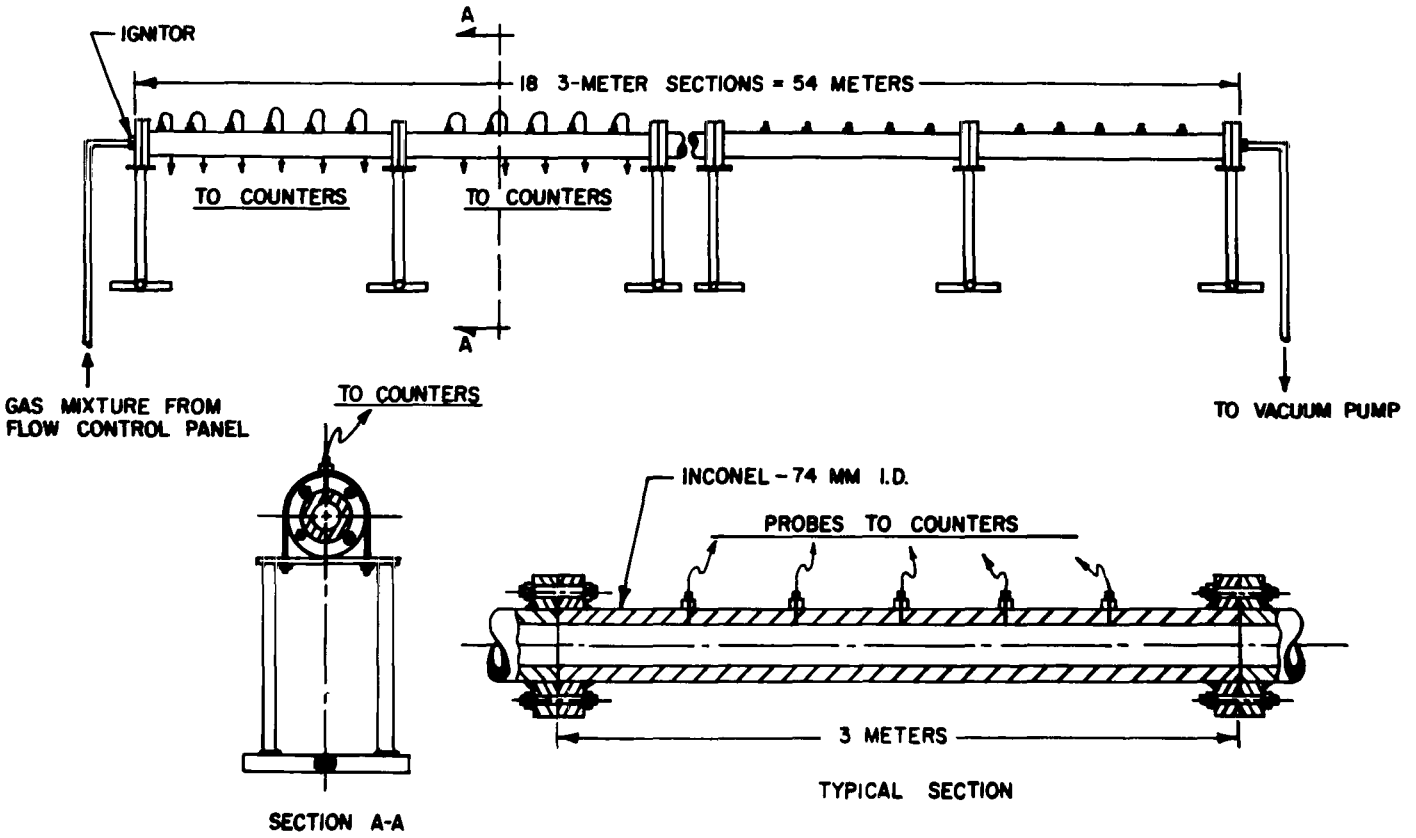

FIG. 1 GENERAL ARRANGEMENT OF 54-METER LONG DETONATION TUBE

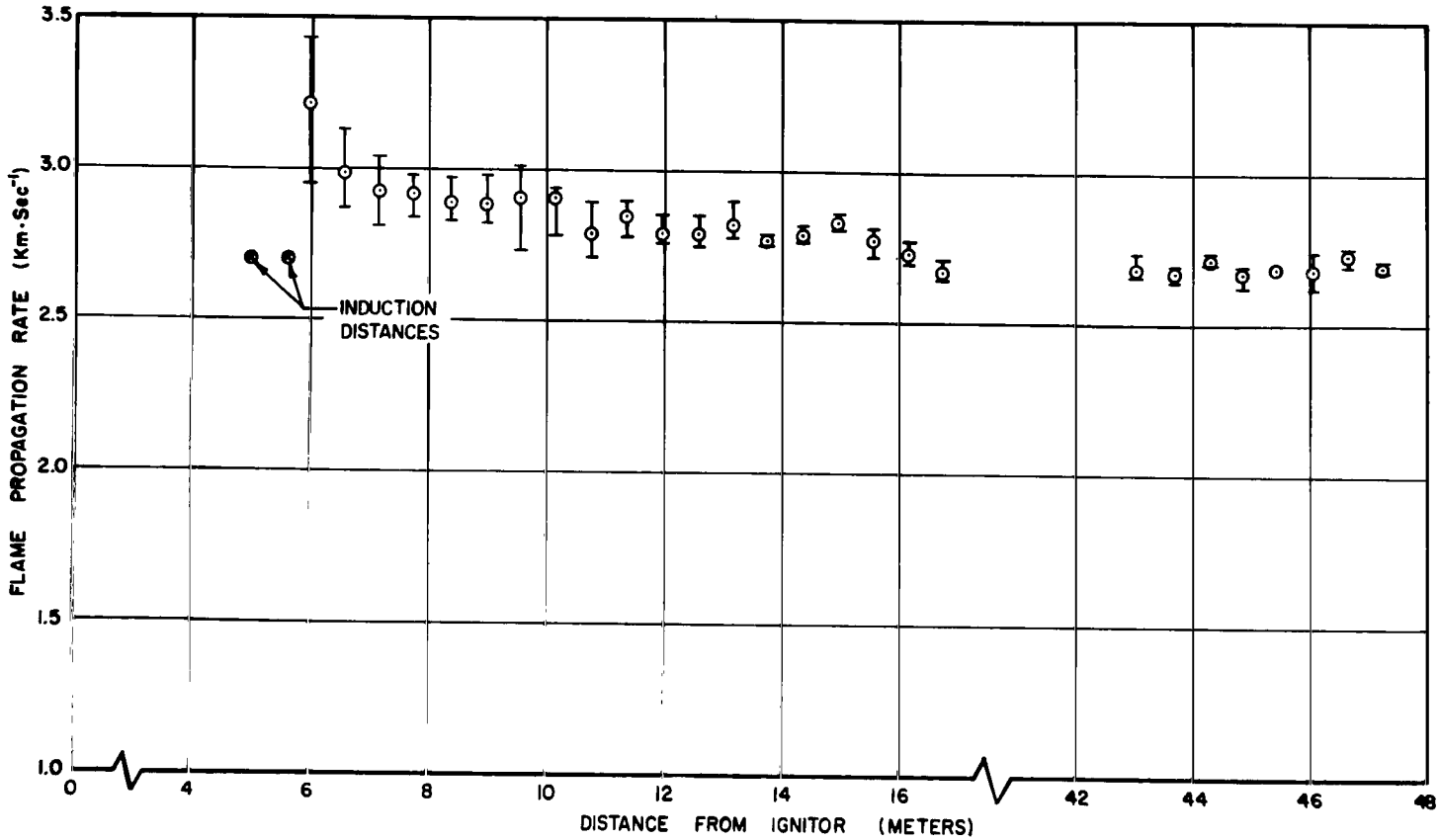

FIG. 2 RATE OF FLAME PROPAGATION IN A H_2 - O_2 MIXTURE;
MOLE % H_2 = 66.67, p_i = 0.2 ATM, t_i = AMBIENT

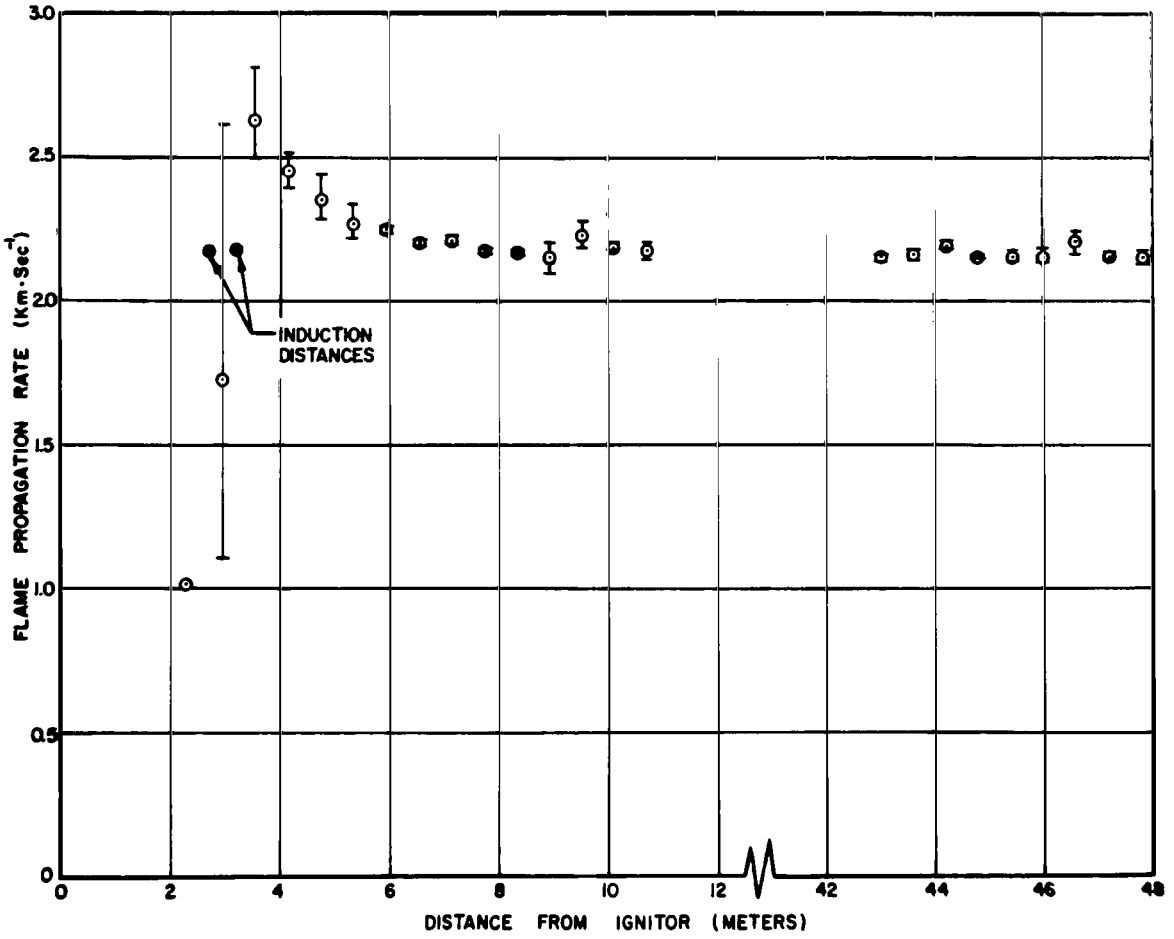

FIG. 3 RATE OF FLAME PROPAGATION IN A H_2 - O_2 MIXTURE;
MOLE % H_2 = 45, p_i = 0.5 ATM, t_i = AMBIENT

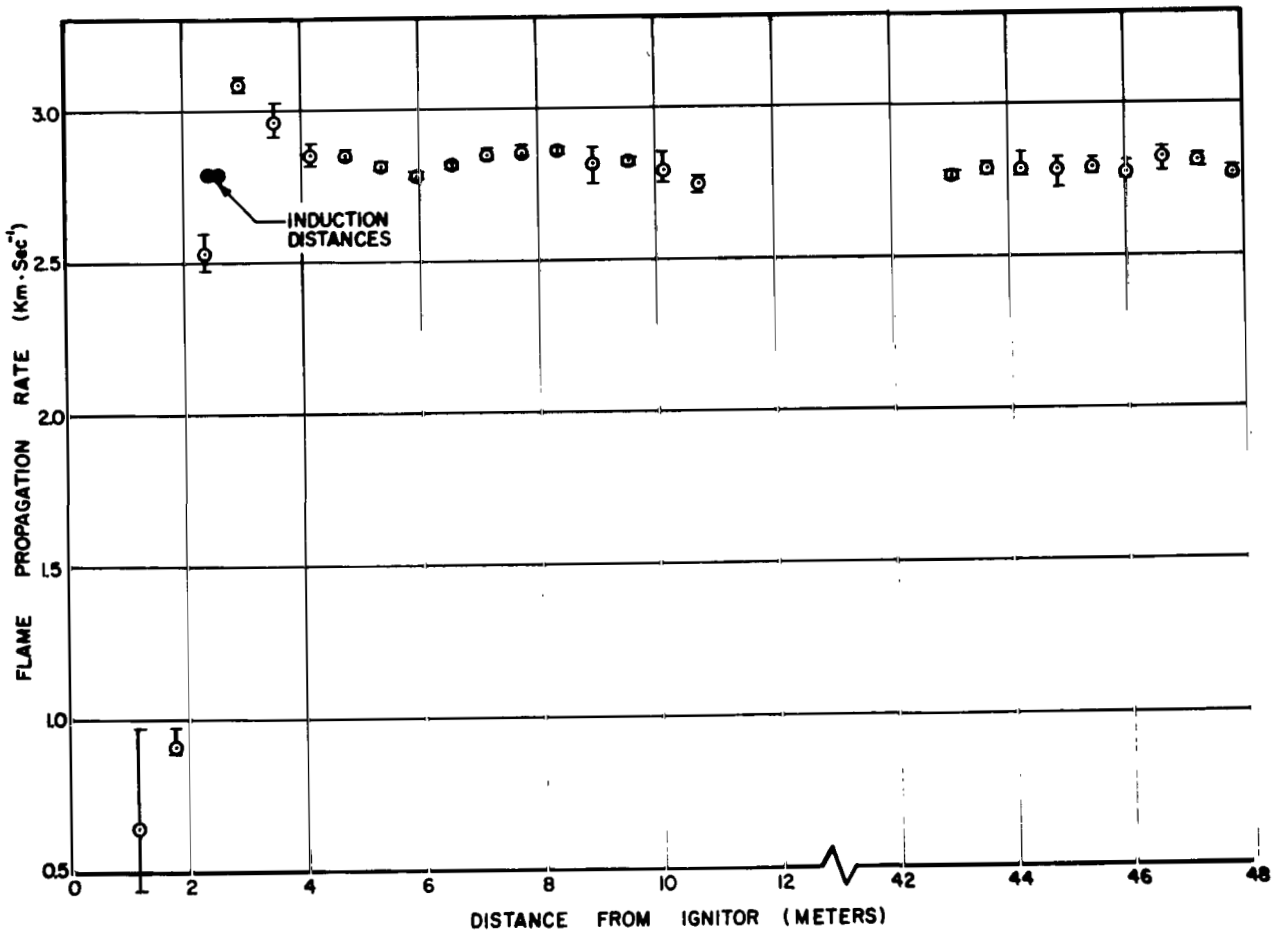

FIG. 4 RATE OF FLAME PROPAGATION IN A H_2 - O_2 MIXTURE;
MOLE % H_2 = 66.67, p_i = 0.5 ATM, t_i = AMBIENT

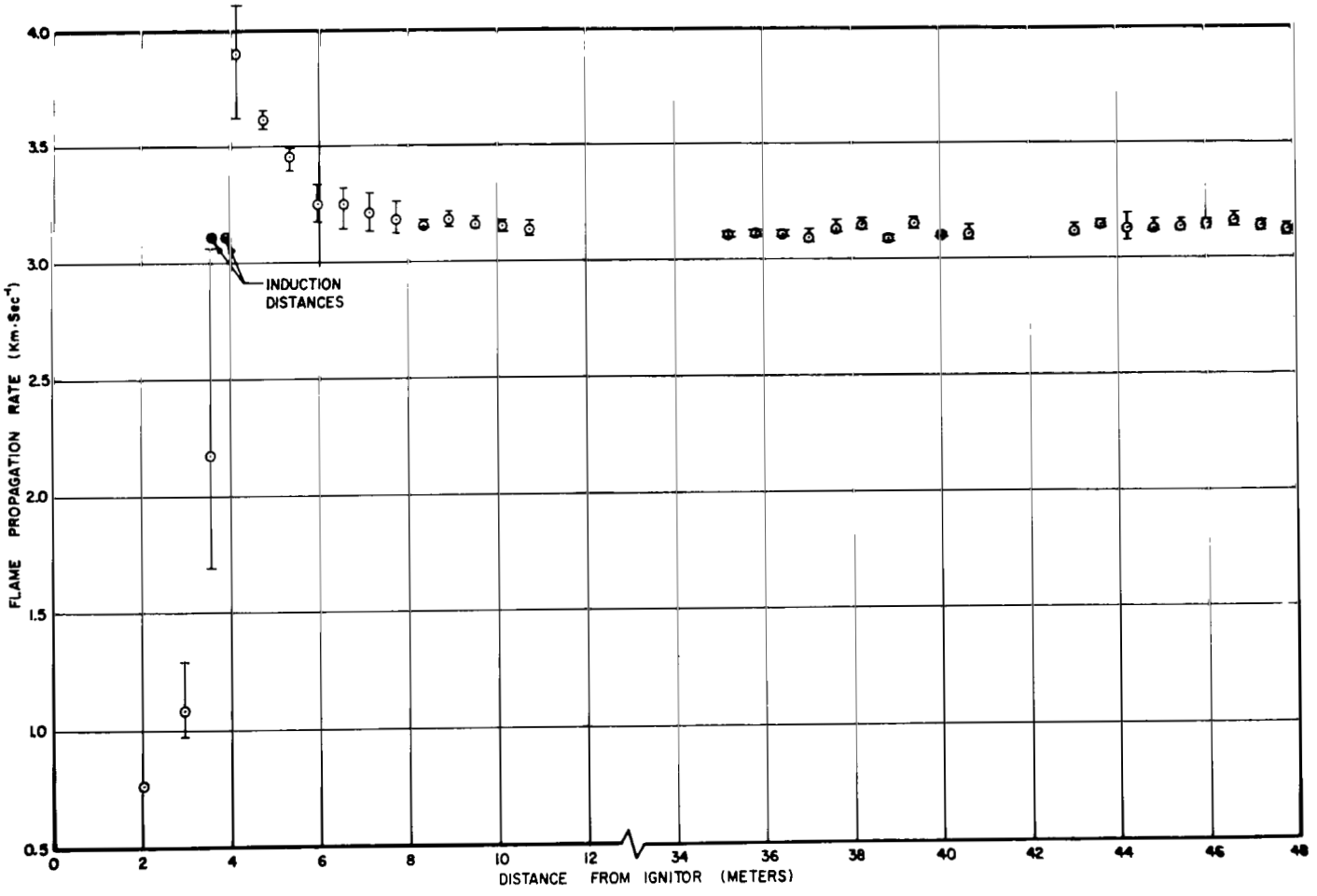

FIG. 5 RATE OF FLAME PROPAGATION IN A H_2 - O_2 MIXTURE;
MOLE % H_2 = 75, p_i = 0.5 ATM, t_i = AMBIENT

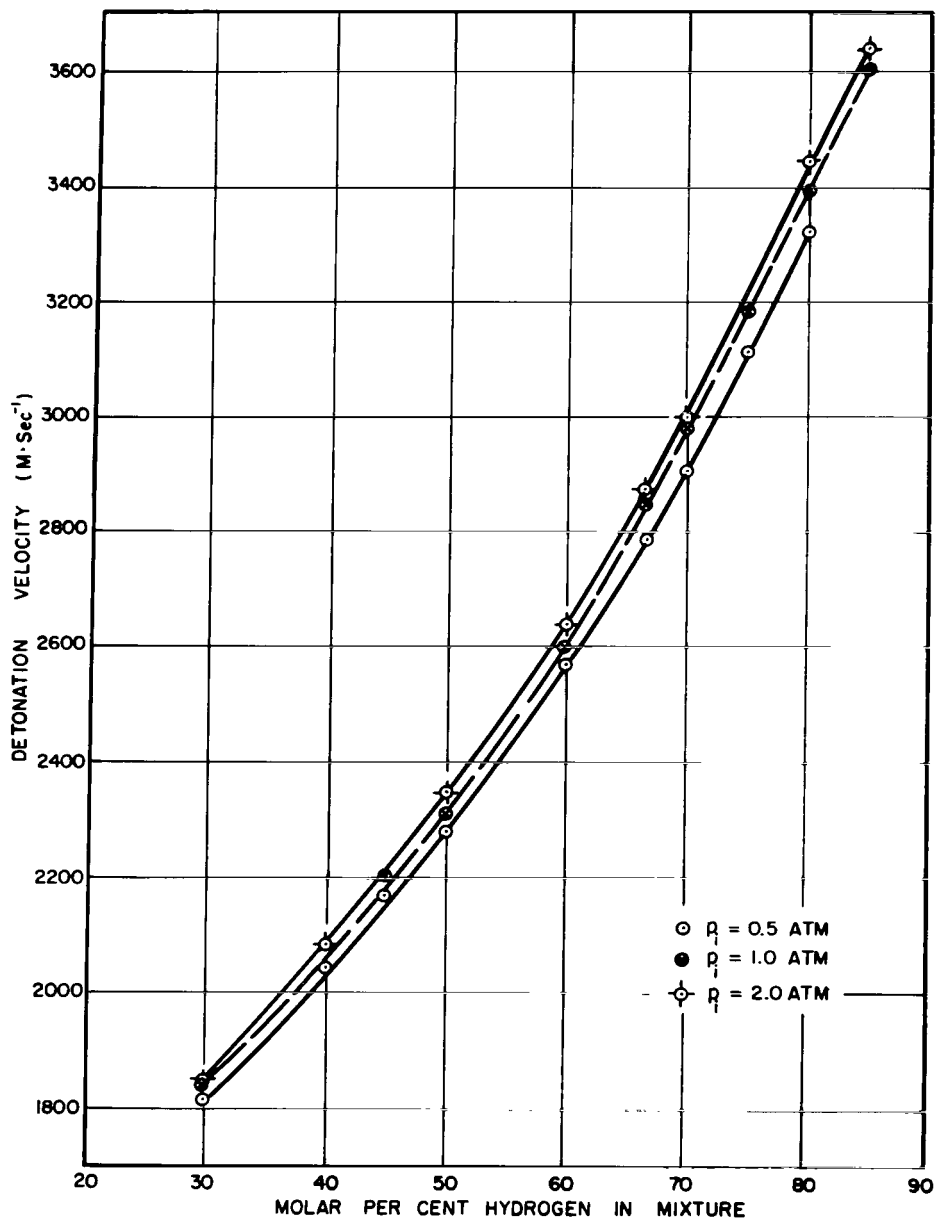

FIG. 6 EXPERIMENTAL DETONATION VELOCITIES IN HYDROGEN-OXYGEN MIXTURES AT INITIAL PRESSURES OF 0.5, 1, AND 2 ATM

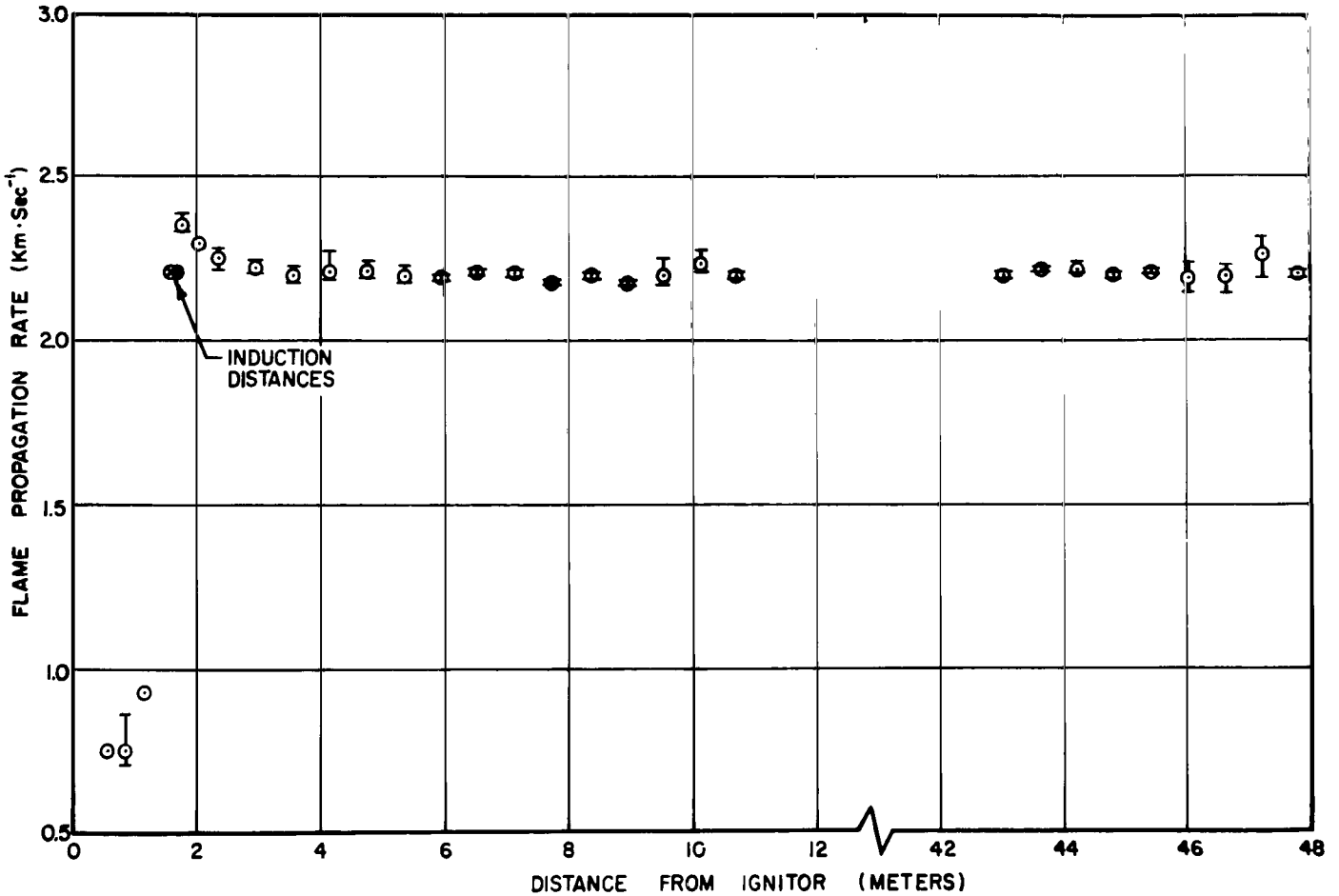

FIG. 7 RATE OF FLAME PROPAGATION IN A H_2 - O_2 MIXTURE;
MOLE % H_2 = 45, p_i = 1 ATM, t_i = AMBIENT

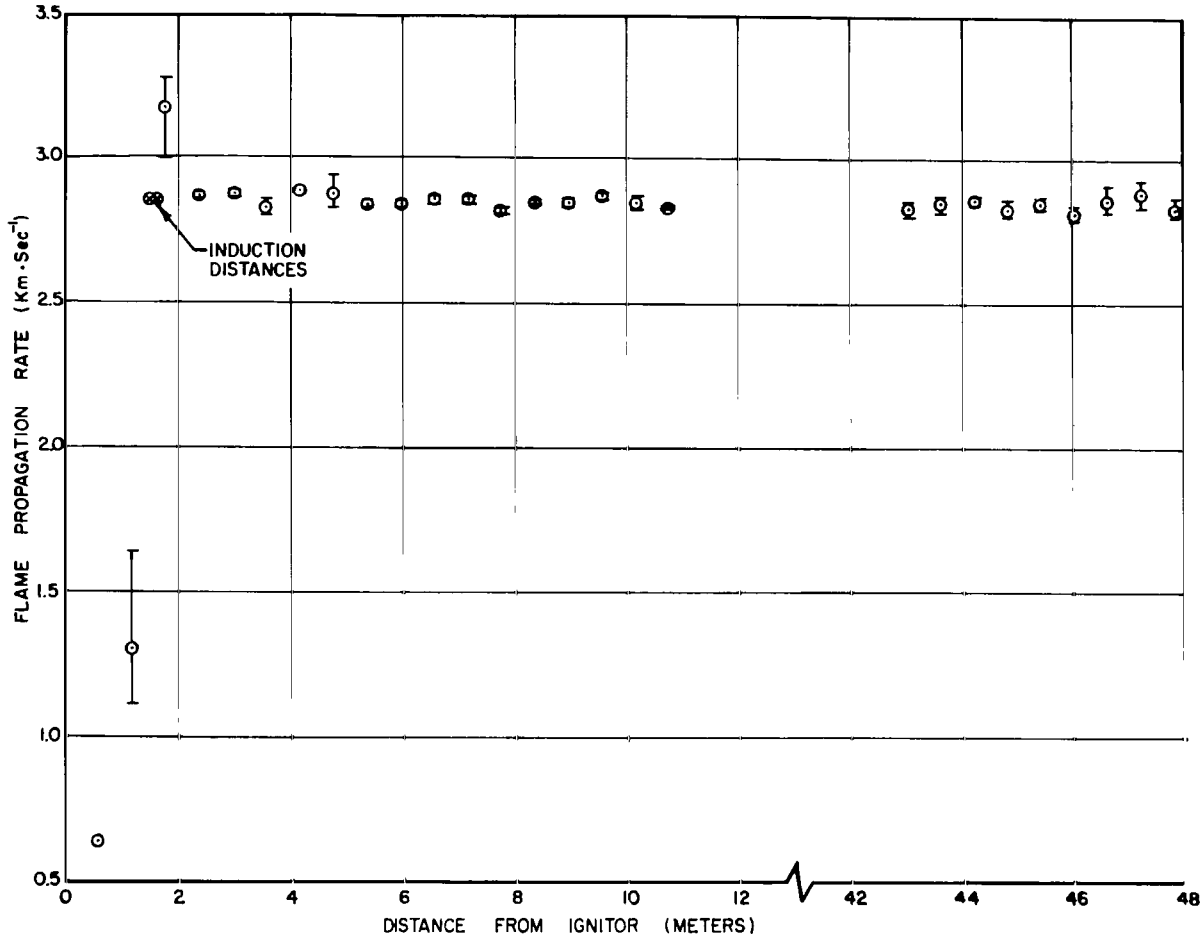

FIG. 8 RATE OF FLAME PROPAGATION IN A H_2 - O_2 MIXTURE;
MOLE % H_2 = 66.67, p_i = 1 ATM, t_i = AMBIENT

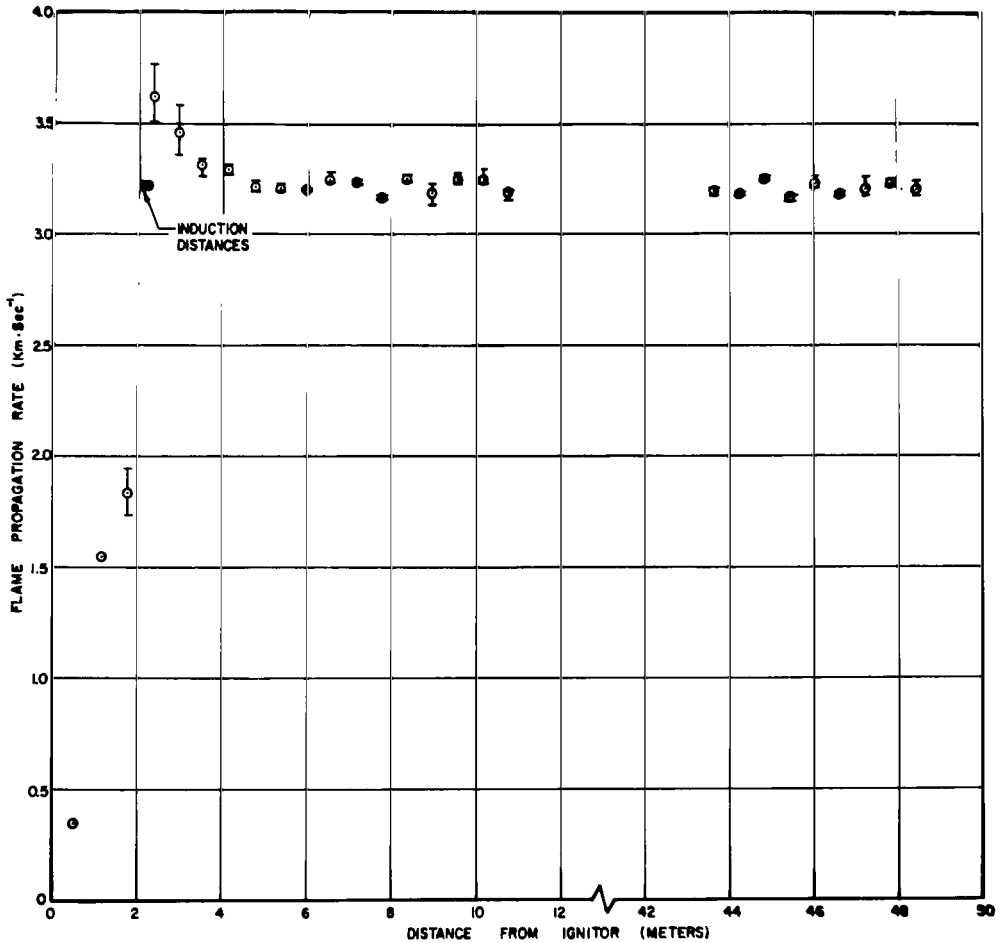

FIG. 9 RATE OF FLAME PROPAGATION IN A H_2 - O_2 MIXTURE;
MOLE % H_2 = 75, p_i = 1 ATM, t_i = AMBIENT

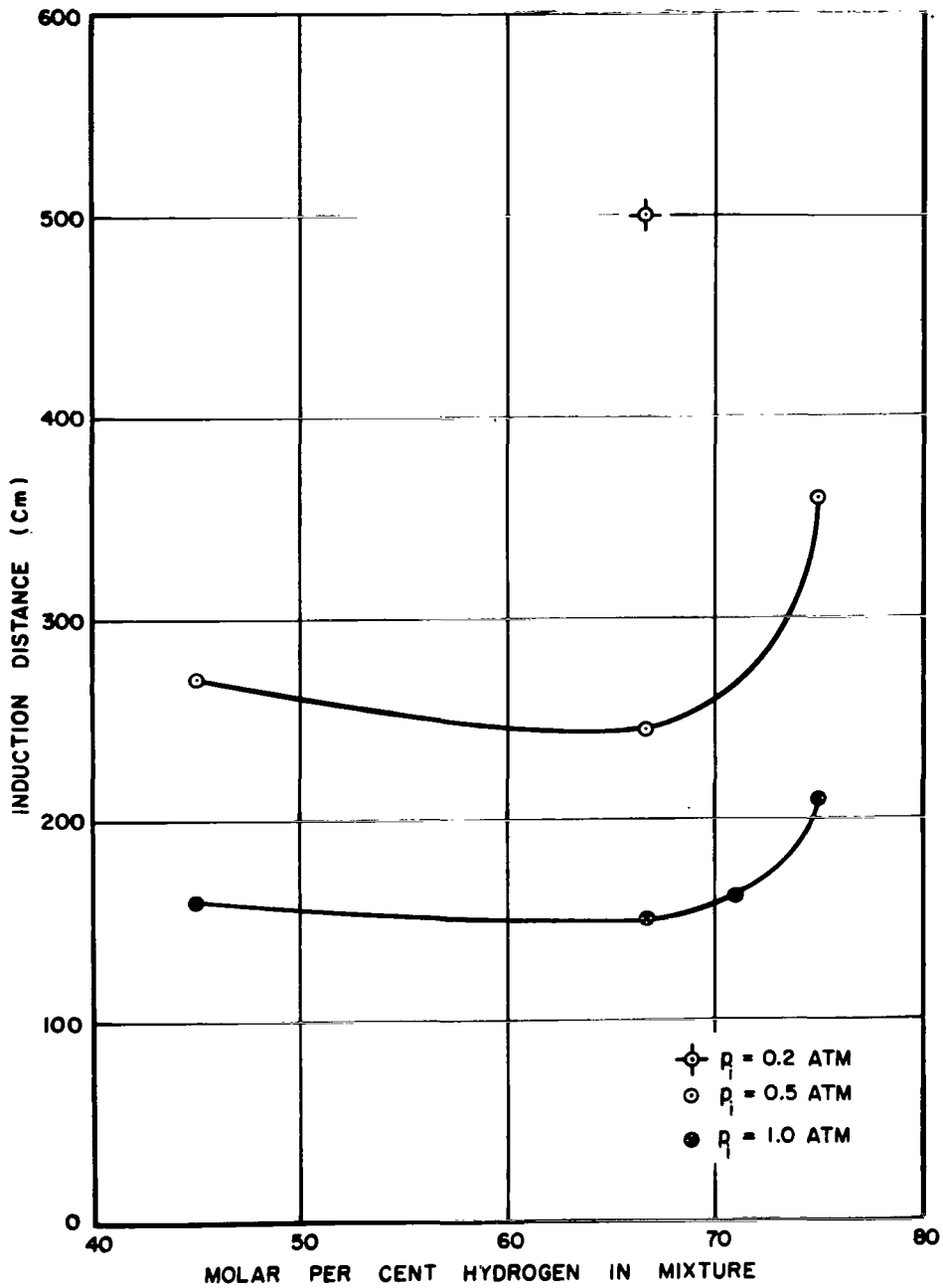

FIG. 10 DETONATION INDUCTION DISTANCES AS A FUNCTION OF FUEL CONCENTRATION FOR VARIOUS INITIAL PRESSURES

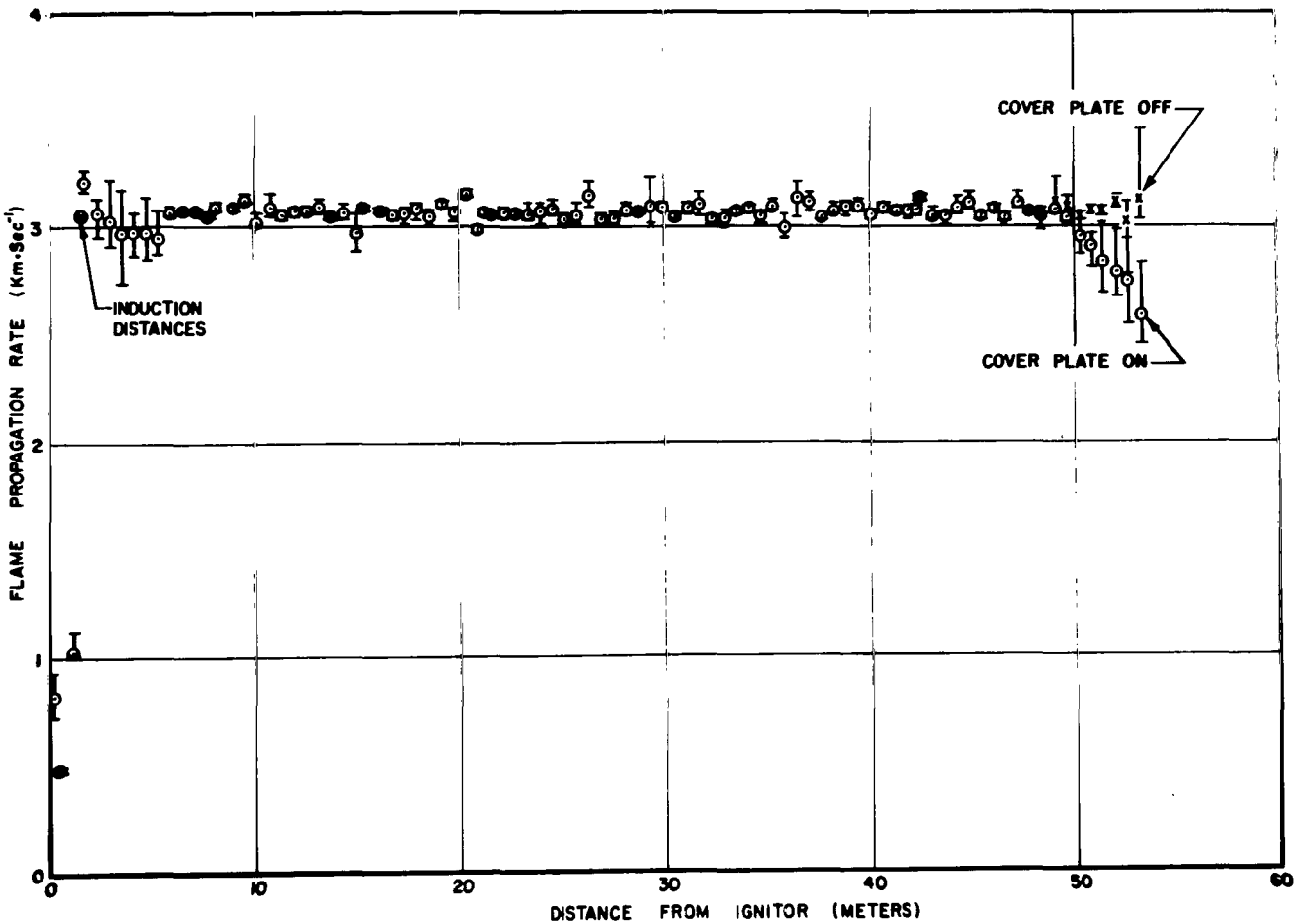

FIG. 11 RATE OF FLAME PROPAGATION IN A H_2 - O_2 MIXTURE;
MOLE % H_2 = 72, p_i = 1 ATM, t_i = AMBIENT

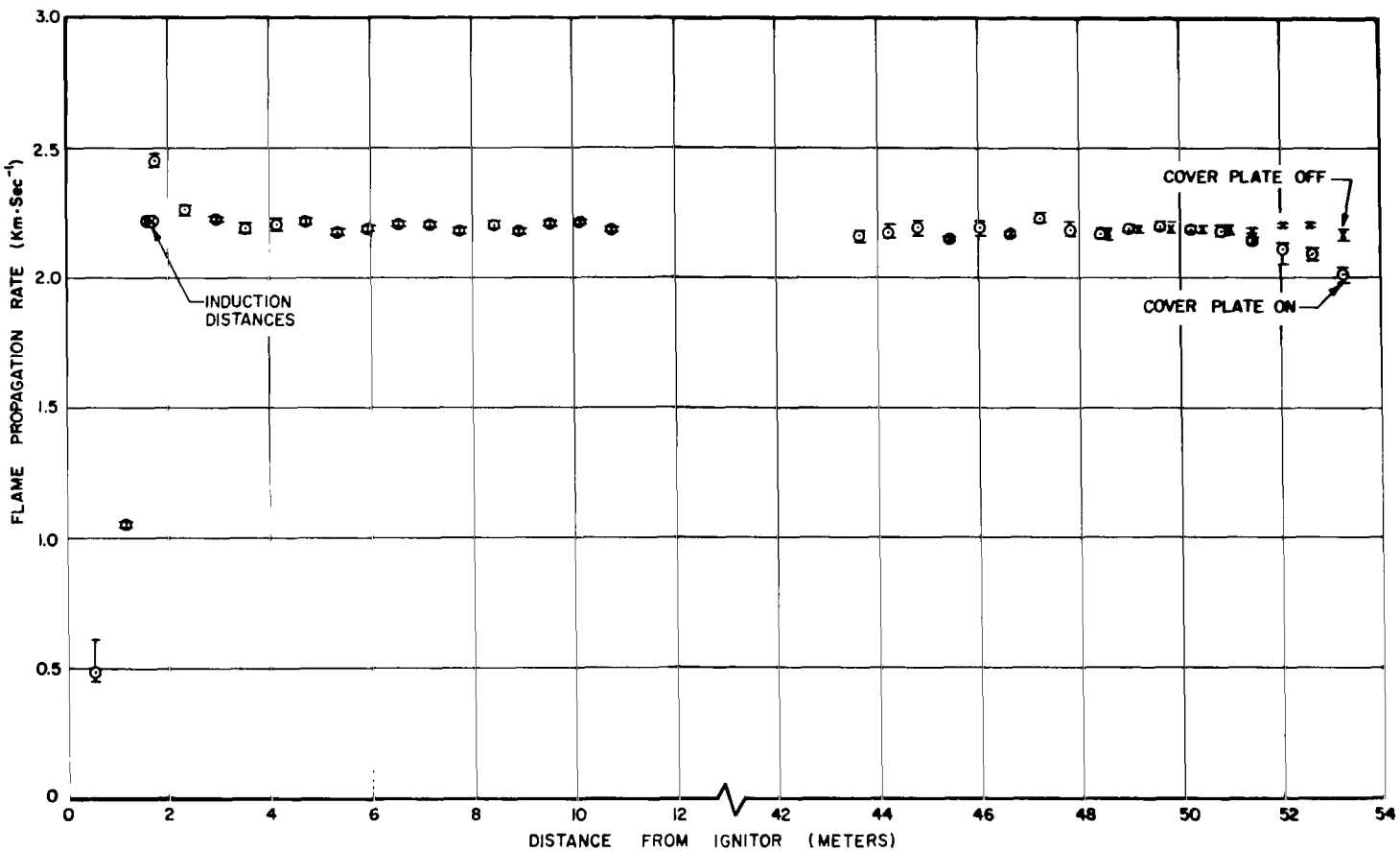

FIG. 12 RATE OF FLAME PROPAGATION IN A H_2 - O_2 MIXTURE;
MOLE % H_2 = 45, p_i = 1 ATM, t_i = AMBIENT

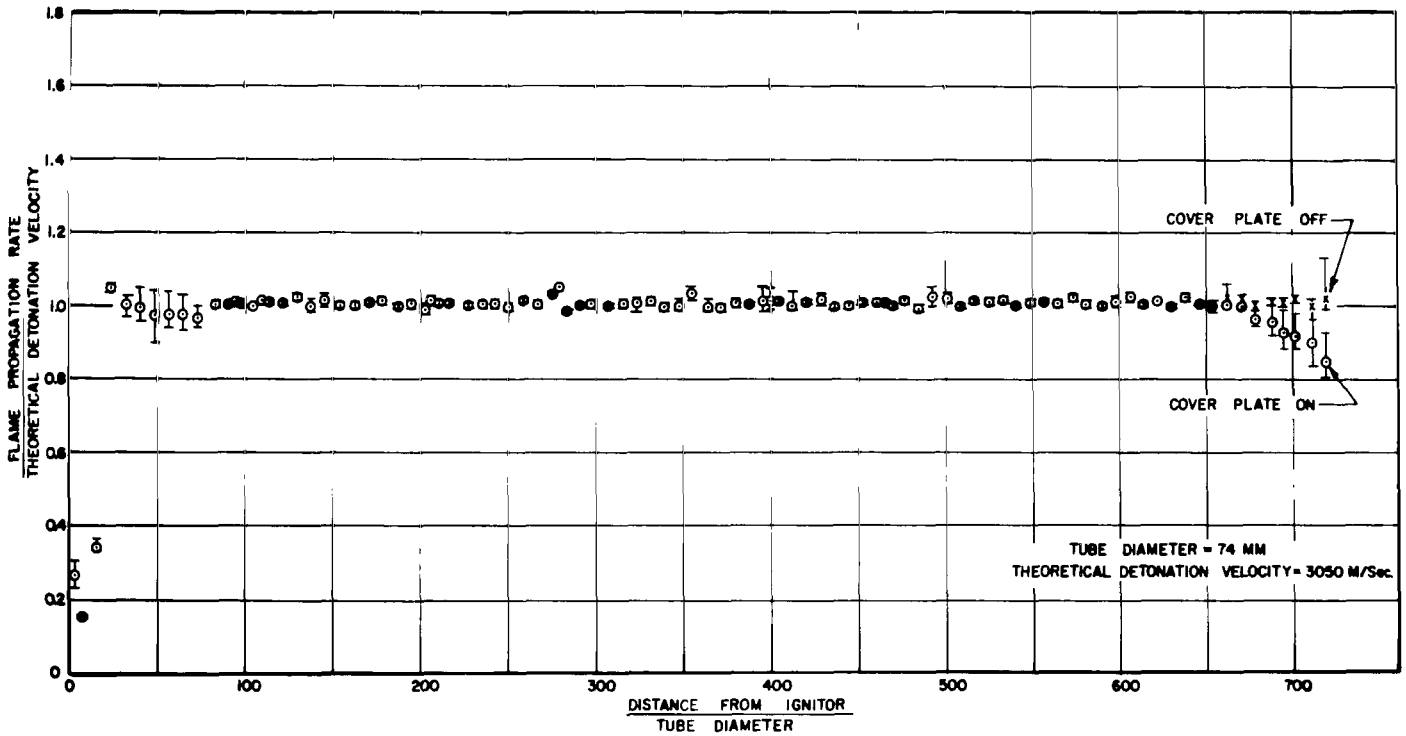

FIG. 13 RATE OF FLAME PROPAGATION (NON-DIMENSIONAL FORM) IN A H_2 - O_2 MIXTURE; MOLE % H_2 = 72, p_i = 1 ATM, t_i = AMBIENT

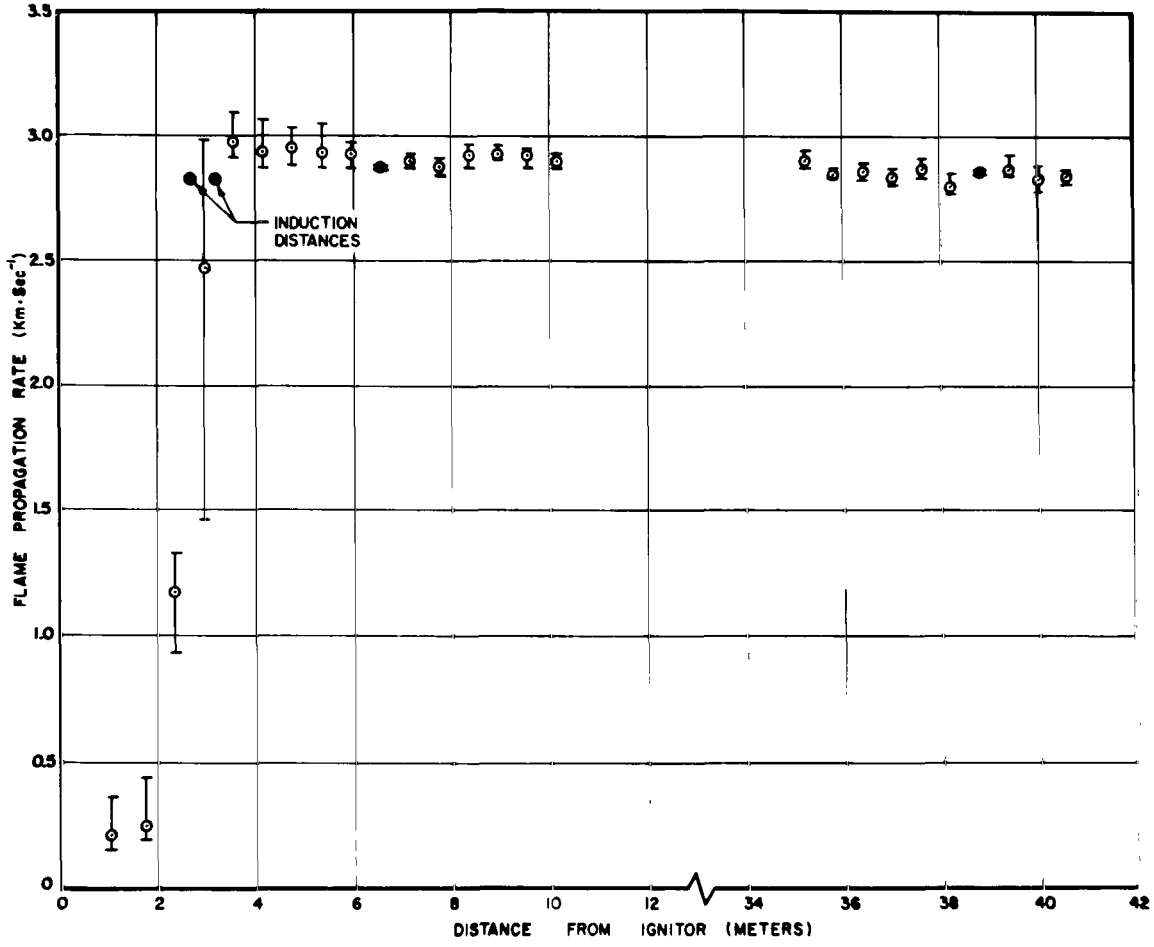

FIG. 14 RATE OF FLAME PROPAGATION IN A H_2 - O_2 MIXTURE; MOLE % H_2 = 66.67, p_i = 1 ATM, t_i = AMBIENT, BOTH ENDS OPEN

2/7/25

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